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BEAM LOSS BY COLLIMATION IN A NEUTRALIZER DUCT

Gordon W. Hamilton
Peter A. Willmann

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Lawrence Livermore Laboratory

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ABSTRACT

Beam fractions lost by collimation in a neutralizer duct are computed in x-x' phase space by using three examples of slab beam distributions under a broad range of duct dimensions, beam half-widths, and beam divergences. The results can be used to design compact neutralizers and to specify beam requirements. The computer code ILOST can be used under a broad range of beam conditions to compute the fraction lost by collimation.

INTRODUCTION

There are several motives for reducing the dimensions of a neutralizing duct, two of which are to economize on space near a large experiment and to develop advanced types of neutral-injection systems. It may even be possible to design a small neutralizing duct for each aperture of a multiple-aperture system. With these motives, and because it is necessary to understand the relationships between duct dimensions, gas flow, beam profiles, and beam losses to optimize the duct design for a particular application, we have computed the fractions of beam losses in a small neutralizing duct for several geometries and beam distributions.

BEAM DISTRIBUTIONS

It is sufficient for our purposes to compute the loss due to beam spread in a two-dimensional, x-x' phase space. In the case of losses due to beam spread in y-y' phase space, these losses can be included by combining the results of two computations. The parameters affecting the beam loss are the half-widths, X and X', of the beam distributions in x-x' space, the analytical form of the beam distributions, and the duct dimensions, D and Z. We have computed the beam-loss fractions as a function of these parameters. The three beam distributions we chose as examples for this computation are sketched in Fig. 1 and are defined as follows:

1. Uniform distribution. The beam density, j, in x-x' space is assumed to be uniform if $-X \leq x \leq +X$ and if $-X' \leq x' \leq +X'$. Here the beam divergence,

$x' = v_x/v_z$, is measured in radians. Normalized so that the total beam current is I, the beam density within these limits is

$$j(x,x') = I/(4XX'). \tag{1}$$

2. Gaussian distribution,

$$j(x,x') = (I/\ XX')\ \exp-\left\{(x/X)^2 + (x'/X')^2\right\}. \tag{2}$$

The normalization factor in Eq. (2) is accurate if j is integrated from $-\infty$ to $+\infty$ in both the x and x' directions. However, we will set the limits at $\pm X_0 = \pm 3X$ and at $\pm X_0' = \pm 3X'$ to cut off the extreme tails of the Gaussian functions. In principle the normalization factor should be increased by 0.5% to compensate for the cut-off, but we did not increase it in this computation.

3. Parabolic distribution,

$$j(x,x') = 2I/(\pi XX')\left\{1 - (x/X)^2 - (x'/X')^2\right\}. \tag{3}$$

This equation defines an elliptical paraboloid of semi-diameters X and X'. We shall require, however, that j is not allowed to be less than zero.

PHASE SPACE DIAGRAMS

Figure 2 shows a rectangular area of x-x' space occupied by the beam as it enters the neutralizer duct. We are considering the area bounded by $-X_0 \leq x \leq X_0$ and $-X_0' \leq x' \leq X_0'$, where $X_0 = 3X$ and $X_0' = 3X'$.
The elliptical contours represent current densities, j, for the distributions (2) or (3).

As the beam passes through the duct it spreads out in the x direction, assuming a straight-line trajectory. Consequently the rectangular area of phase space becomes deformed to the shape of a parallelogram as shown in Fig. 3. The deformation is a maximum of ZY_0', where Z is the length of the duct.

Now if a collimator of width D is imposed, the area of phase space cut off consists of two triangles of base b and altitude h where $b = X_0 + ZX_0' - D/2$ and $h = b/Z$.

To compute the lost beam current, we must integrate j over the area of the two cut-off triangles. We will first transform the phase space back to the condition of the beam at the entrance of the neutralizer, as in Fig. 2. We will use Fig. 4 to determine the limits of the integration;

$$I_{lost} = 2 \int_{X_0'-h}^{X_0'} \left[dx' \int_{x_1}^{X_0} j(x,x')\, dx \right] . \tag{4}$$

Here the point (x_1, x_1') is a variable point on the diagonal line passing through two fixed points: $\left\{X_0,\ (X_0'-h)\right\}$ and $\left\{(X_0-b),\ X_0'\right\}$.

This gives us the equation of the diagonal line, which enables us to carry out the integration (4):

$$x_1 = X_0 - Z(x_1' - X_0' + h). \tag{5}$$

INTEGRATIONS IN PHASE SPACE

We have programmed Eqs. (1) through (5) and thereby have numerically computed the ratio I_{lost}/I for the three distributions as a function of the input conditions X, X', D, and Z. As a check we have carried out the same integration analytically for the example of the uniform distribution.

The analytic integration is straightforward except for the fact that the triangular area of phase space becomes a trapezoidal area if $b > 2X_0$. It is necessary to include this correction for the analytical solution but not for the numerical solution. This correction does not affect the numerical integration, because the integrand, j, is zero in the region affected.

RESULTS

The computer output consists of tables and graphs showing the ratio I_{lost}/I for each distribution as a function of X, X', D, and Z. Figure 4 shows an example of the graphic output.

A more practical presentation of the output shows the allowable beam divergence, X', as a function of the allowable beam loss and the other parameters. This is shown by Fig. 5, in which it was assumed that only 5% beam loss is allowable and the duct aspect ratio L/D was required to be at least 20. In this example ($X = 2$ mm) the allowable beam divergence increases with duct width, D, and attains a maximum of 31.5 mrad for the parabolic beam distribution.

Figure 6 should not be used to make comparisons between the beam-loss fractions of the three distributions, because X and X' are defined differently for the three examples. A large fraction of the Gaussian beam is outside the limits of X and X', while the other two distributions are completely contained within them. It is our intention that the user of this program would determine which beam distribution best fits his conditions and use the appropriate computation.

EO/sc

FIGURE CAPTIONS

FIG. 1. Three examples of slab beam distributions, where $j(x,x')$ is the beam-current distribution in x-x' phase space. Here the current density, $j(x,x')$ is normalized so that X is the half-width and X' is the beam divergence as defined below. The current density, $j(x,x')$ is normalized so that I is the total beam current integrated over phase space. (a) Uniform beam distribution: $j(x,x') = I/(4XX')$ if $-X \le x \le X$ and $-X' \le x' \le X'$; $= 0$ otherwise. (b) Gaussian beam distribution: $j(x,x') = (I/\pi XX') \exp-[(x/X)^2 + (x'/X')^2]$ if $-X_0 \le x \le X_0$ and $-X_0' \le x \le X_0'$; $X_0 = 3X$; $X_0' = 3X$; $j(x,x') = 0$ otherwise. (c) Parabolic beam distribution: $j(x,x') = (2I/\pi XX')\,(1 - (x/X)^2 - (x'/X')^2)$ but j is never less than zero.

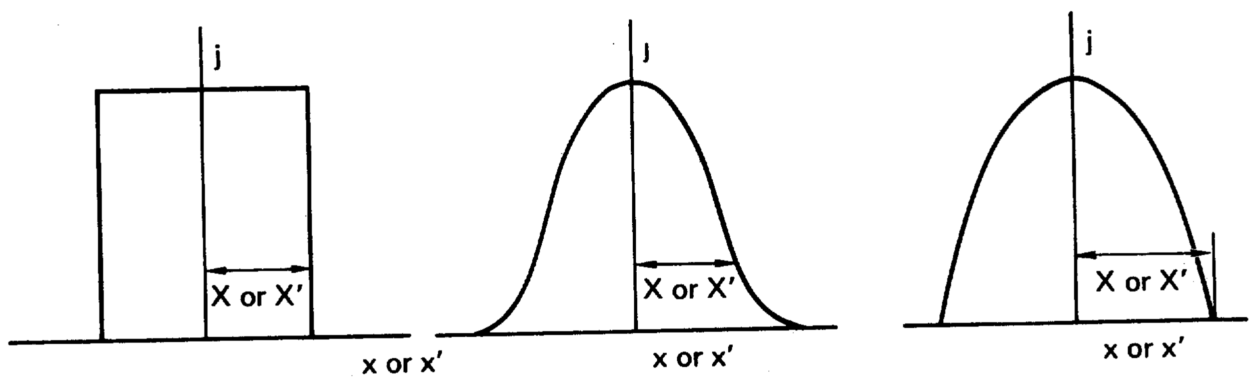
FIG. 2. Phase space occupied by a slab beam in x-x' coordinates at the entrance of a neutralizer duct. The elliptical contours are lines of equal $j(x,x')$.

FIG. 3. Phase space occupied by a slab beam after it spreads out in the x direction and passes through a neutralizer duct. The maximum deformation of phase space is ZX_0'. The area of phase space cut off if a collimator of width D is imposed is represented by two triangles of base b and altitude h.

FIG. 4. Phase space of Fig. 3, including the two triangles cut off by the collimator, transformed back to the entrance of the neutralizer. The fraction of lost beam is computed by integrating $j(x,x')$ over the area of the triangles.

FIG. 5. Beam loss fraction I_{lost}/I as a function of beam divergence X' for the three distributions, using as an example X = 2 mm, D = 10 mm, Z = 200 mm: (a) uniform distribution; (b) Gaussian distribution; (c) parabolic distribution.

FIG. 6. Allowable beam divergence, X', as a function of D with a 5% allowable beam loss and a duct aspect ratio Z/D = 20.



a. Uniform b. Gaussian c. Parabolic

FIG. 1

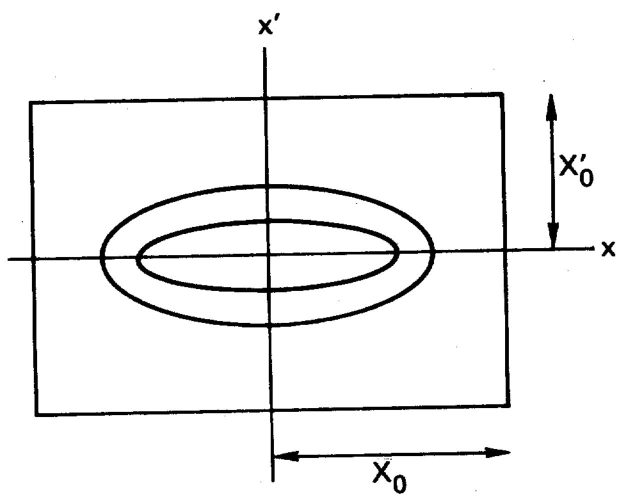


FIG. 2

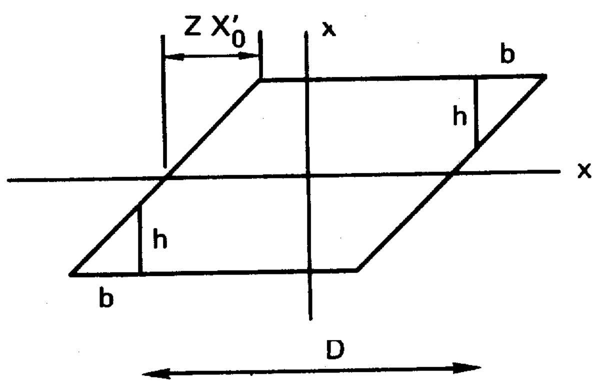


FIG. 3

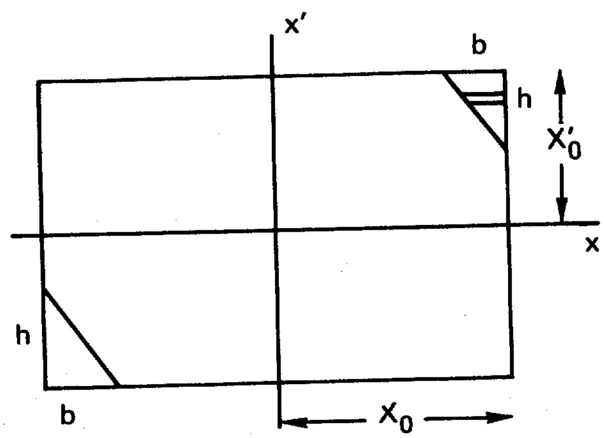


FIG. 4

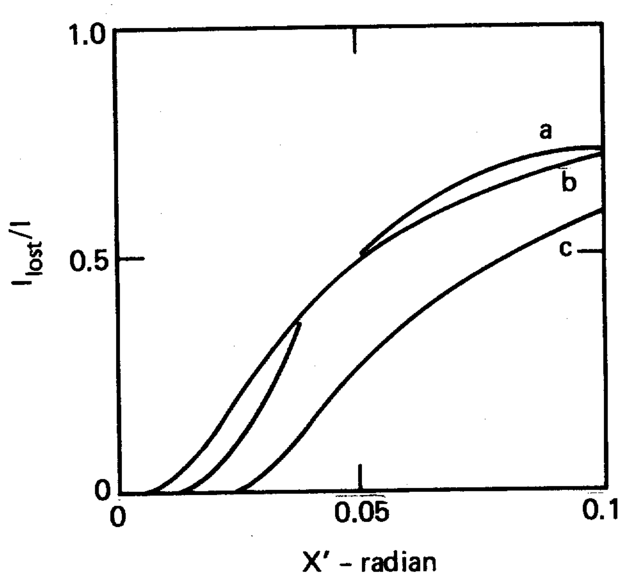


FIG. 5

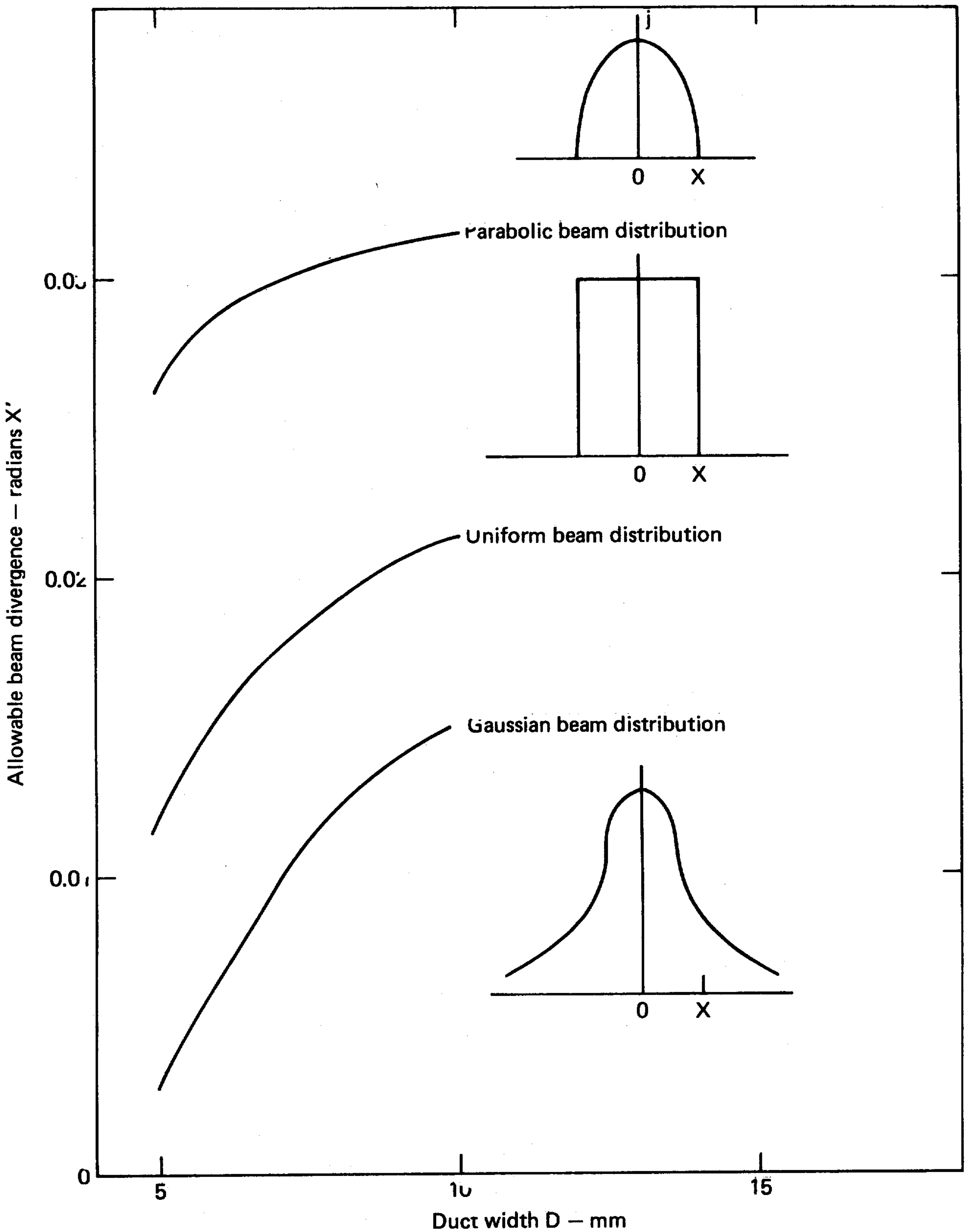

j
0
X
Parabolic beam distribution
0.03
0
X
Uniform beam distribution
0.02
Gaussian beam distribution
0.01
0
X
0
5
10
15
Duct width D — mm
Allowable beam divergence — radians X'

FIG. 6